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EXPLORING THE OUTER SOLAR SYSTEM WITH THE ESSENCE SUPERNOVA SURVEY

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ABSTRACT

We report the discovery and orbit determination of 14 trans-Neptunian objects (TNOs) from the ESSENCE Supernova Survey difference imaging dataset. Two additional objects discovered in a similar search of the SDSS-II Supernova Survey database were recovered in this effort. ESSENCE repeatedly observed fields far from the Solar System ecliptic ($-21^\circ < \beta < -5^\circ$), reaching limiting magnitudes per observation of $I \approx 23.1$ and $R \approx 23.7$. We examine several of the newly detected objects in detail, including 2003 UC$_{414}$ which orbits entirely between Uranus and Neptune and lies very close to a dynamical region that would make it stable for the lifetime of the Solar System. 2003 SS$_{422}$ and 2007 TA$_{418}$ have high eccentricities and large perihelia, making them candidate members of an outer class of trans-Neptunian objects. We also report a new member of the "extended" or "detached" scattered disk, 2004 VN$_{112}$, and verify the stability of its orbit using numerical simulations. This object would have been visible to ESSENCE for only $\sim 2\%$ of its orbit, suggesting a vast number of similar objects across the sky. We emphasize that off-ecliptic surveys are optimal for uncovering the diversity of such objects, which in turn will constrain the history of gravitational influences that shaped our early Solar System.

Subject headings: surveys — methods: data analysis — Kuiper Belt

1. INTRODUCTION

The discovery of the accelerating universe in 1998 (Riess et al. 1998; Perlmutter et al. 1999, ; for a review, see Filippenko 2005) has given rise to a large number of next-generation surveys searching for distant supernovae to probe the cosmological dark energy. These surveys are typically undertaken with wide-field imaging cameras to ensure areal coverage broad enough to find significant numbers of supernovae, and use moderate to large-aperture telescopes to probe for faint supernovae at high redshifts. A given supernova is typically sampled every few days to resolve its brightness and color evolution.

Within a given night, one of the most frequent contaminants to supernova searches is foreground Solar System objects, which leave a similar new-object signature in every image containing them. In addition, since supernova surveys tend to reach much deeper than dedicated Solar System surveys, the majority of these moving objects will be uncatalogued. For this reason, multiple temporal observations of a supernova candidate are required to verify its spatial persistence before scheduling it for spectroscopic follow-up observations. Multiple images may be taken on a single night to ensure that any Solar System objects show slight astrometric motion (trans-Neptunian objects have reflex motions of $\sim 1''$ hr^{-1}), or on different nights, allowing the Solar System object to

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have moved significantly (instead proving to be a contaminant in some other location). These objects are typically ignored by the surveys, but given the integrated amount of data available, provide the opportunity for significant advances in our understanding of the Solar System.

2. METHODS

The observing strategy for the ESSENCE supernova survey is described by Miknaitis et al. (2007). These observations have been optimized for the characterization of the dark energy equation-of-state parameter w (e.g., Padmanabhan 2003). In summary, the strategy was to take two images of a given field per night using the Blanco 4-m telescope plus MOSAIC-II imaging camera at the Cerro Tololo Inter-American Observatory (CTIO). One image was taken in the I band and the other in the R band, typically separated by $\sim$60 min. The exposure times lead to approximate limiting 5σ magnitudes of $I \approx 23.1$ and $R \approx 23.7$. The survey has thirty-two 0.36 $\deg^2$ fields, each of which was observed roughly every fourth night. ESSENCE images were obtained for 20 d around new moon for six years, from 2002 to 2007, during 3 consecutive months, usually October through December. This observing cadence is serendipitously useful for the study of TNOs. It has sufficiently large intra-night spacing to allow slight astrometric motion, yielding an instantaneous angular velocity. It also provides enough intra-month observations to recover a given object several times per lunation, allowing us to link pairs of observations that have consistent motion vectors.

ESSENCE uses a real-time difference imaging pipeline (`Photpipe`; Smith et al. 2002) that operates at the base camp of CTIO. Images are reduced and differenced immediately after acquisition, and information on the detections found in the difference images is posted to the internet for review by a team member. Objects clearly in motion are rejected from this visual analysis, and objects not confirmed in follow-up observations are similarly ignored. It is this set of data that we wish to mine for distant Solar System objects.

In this effort, we searched through *all* detections reported by ESSENCE's `Photpipe` difference imaging pipeline for the 6 seasons of ESSENCE operations. We kept all observations that were positive-flux excursions, and which had a signal-to-noise ratio of at least 5. This yielded in total 3.7×10^6 independent detections. If we naively attempted to link all permutations of these N observations into tracks M observations long, the problem would scale as N^M. This would very quickly become computationally intractable. It is primarily for this reason that such studies have not been attempted in the past. However, new methods of parsing and organizing these data allow us to rapidly prune infeasible matches, allowing computational scalings as fast as $N \log(N)$ (Kubica et al. 2007).

We used a prototype of the software developed by Kubica et al. (2007) to link the pairs of R and I-band observations each night into $\sim$ 1-hr "tracklets," as well as to link these tracklets across nights, into potential orbits called "tracks." For computational efficiency, we split the data by observing season for the intra and inter-night linkages. For intra-night linkages, we required at least 2 detections whose separations implied angular velocities less than 0.05° d^{-1}, which would reject objects at opposition and on circular orbits having semimajor axes $a < 15$ Astronomical Units (AU). This process yielded 1.6×10^5 tracklets, which were next linked between nights. For these inter-night linkages, we allowed tracks with a maximum angular velocity of 0.05° d^{-1}, maximum angular acceleration of 0.03° d^{-2}, and supporting observations on at least 4 nights. At time of maximum angular acceleration 90° from opposition, the acceleration cut would reject objects on circular orbits with $a \lesssim 35$ AU. However, the majority of our observations were taken within 40° of opposition, where this cut would reject objects with $a \lesssim 20$ AU. These particular limits were chosen as a compromise between the goal of searching for TNOs and the computational burden of fitting additional spurious tracks. This process yielded 3.2×10^6 quadratic tracks as potential orbits.

We fit each track using the software of Bernstein & Khushalani (2000, hereafter BK00) to weed out linkages that do not correspond to Keplerian motion. We removed all tracks with best-fit semimajor axes $a < 10$ AU, since the software model uses a linear set of equations only valid for distant objects. We rejected all fits whose χ^2 per degree of freedom was greater than 2.0. Given each preliminary orbit, we searched again through the difference imaging detections for matches on nights where there were data in only one of the two passbands. These additional points helped to validate as well as extend each orbital arc. This winnowing process yielded 16 acceptable orbits with an average of 15 observations per object, and an average orbital arc of 50 d, excluding 6 objects that were detected in multiple seasons. The RMS deviations of our measured positions from the best-fit models is approximately $0.1''$.

A summary of the objects detected and their orbital parameters is given in Table 1. We list the BK00 fit parameters and uncertainties from the ESSENCE data alone, including semi–major axis a', eccentricity e', and inclination i'. We include the χ^2 per degree of freedom of the fit and length of ESSENCE's orbital arc in years. The χ^2 values are artificially small because the BK00 software overestimates the astrometric uncertainty per measurement at $0.2''$. We also list the most recent orbital parameters from the MPCORB database a, e, and i, as well as the absolute magnitude H, defined as the apparent visual magnitude at zero phase angle and 1 AU distance from both the Earth and Sun.

3. RESULTS

While the yield from this search is modest in terms of the number of objects detected, the search is noteworthy in that half of the ESSENCE fields are significantly off the ecliptic ($-21^\circ < \beta < -5^\circ$). This provides a higher sensitivity to high-inclination objects than normal ecliptic surveys. As Table 1 shows, $\sim$ 70% of our objects have inclinations greater than 10°. This is a larger fraction than that found in a similar search of the SDSS-II Supernova Survey data ($\sim$ 40%) by Becker et al. (2008), and significantly larger than the fraction of high-inclination objects in the known sample of all distant objects ($\sim$ 5%).

The ESSENCE observing strategy is significantly different than in typical TNO surveys; its temporal cadence is designed to optimally constrain lightcurves of distant supernovae as opposed to discover and follow-up Solar System bodies (e.g. Jones et al. 2006). The common wisdom borne of these past surveys is that at least two oppositions worth of data are needed before one can compute a reliable orbit or begin to distinguish between dynamical classes. We re-examine these presumptions to ascertain the reliability of our single-opposition orbits.

The primary issue to be resolved is whether or not a single season of data taken at ESSENCE's observing cadence is sufficient to distinguish between different dynamical classes of objects. To examine the accuracy of our single-opposition orbits, we first divide the data from our 6 multi-opposition objects into subsets delimited by observing season. We then fit these subset tracks with the BK00 software and compare the subset fit parameters a, e, and i to the solution from the full fit, normalizing the difference by the associated uncertainty from the subset fit. We find that the software actually *overestimates* the uncertainties on single-opposition parameters, which have a mean offset from their multi-opposition fits of $\sim 0.3\sigma$. By reducing the astrometric measurement uncertainties to a more representative $0.1''$ we find mean offsets of $\sim 0.6\sigma$. The implication is that our single-opposition orbits are relatively robust and that BK00 appear to do a conservative job at assigning uncertainties to the orbital parameters.

The dynamical classification and interpretation of TNOs typically requires numerical simulations of their nominal orbits, as well as the orbits of an ensemble of clones that have orbits consistent with the accumulated astrometry (e.g., Lykawka & Mukai 2007; Morbidelli et al. 2008). Such an effort is beyond the scope of this paper. However, qualitative classifications can be drawn from an object's orbital parameters, with the caveat that some single-opposition orbits may be significantly affected by assumptions inherent to the fitting software and may change characteristics in a non-linear fashion with additional observations. Below we examine the dynamical implications of 2003 UC$_{414}$ (one opposition), 2003 SS$_{422}$ (one opposition), 2007 TA$_{418}$ (two oppositions), and 2004 VN$_{112}$ (two oppositions).

3.1. *2003 UC$_{414}$*

The BK00 orbital parameters and those extracted from the MPCORB database are in stark disagreement for 2003 UC$_{414}$, as seen from Table 1. The source of this discrepancy is unclear. To resolve this issue, we turn to a third independent package, `OrbFit`, developed by Milani (1999). Its orbital solution has $a = 25.9 \pm 0.1$ AU, $e = 0.08 \pm 0.02$, and $i = 26.4 \pm 0.4$ degrees, very much in agreement with the BK00 solution, which we adopt here.

The orbit of 2003 UC$_{414}$ is interesting because it has a low eccentricity and is positioned nearly halfway between Uranus and Neptune. Given the strong gravitational perturbations caused by the giant planets, this intuitively seems like a very unstable orbital configuration. In fact, there are only two known similar objects with orbital arcs longer than two days : (160427) 2005 RL$_{43}$ (Becker et al. 2008) and 2000 CO$_{104}$. Dynamical simulations suggest that there are two islands of stability between Uranus and Neptune, with $a \sim 24.6$ and 25.6 AU (Holman 1997). The dynamical lifetimes of objects in these regions is $\sim 10^9$ years. Any confirmed members would provide additional constraints on models of Solar System evolution that include violent dynamical instabilities in the orbits of Uranus and Neptune (e.g. Levison et al. 2007), which should depopulate these regions. Because of 2003 UC$_{414}$'s relatively short arc and uncertain orbital parameters, more observations of this particular object are necessary to ascertain if it lies within either of these regions.

3.2. *2003 SS$_{422}$ and 2007 TA$_{418}$*

Both 2003 SS$_{422}$ and 2007 TA$_{418}$ have high-eccentricity (0.50 and 0.80, respectively), non-Neptune interacting (q = 36.2 and 39.2 AU) orbits. Emel'yanenko et al. (2003) have examined a similar set of objects, selected by $a > 49.9$ AU and $q > 30.9$ AU, integrating their orbits and those of clones for 4.5 Gyr. They find that a substantial portion of such high-eccentricity objects do not reach the near-Neptune region in the age of the Solar System, making the scattered-disk population an unlikely origin for these objects. There appears to be a soft cutoff of $q \approx 35$ AU between stable and unstable behavior. Both 2007 TA$_{418}$ and 2003 SS$_{422}$ are near this threshold, and must be analyzed in a similar manner to determine their stability. 2003 SS$_{422}$ is particularly interesting in this regard, having a larger semimajor axis and eccentricity than any object in the Emel'yanenko et al. (2003) study other than 2000 CR$_{105}$ (Gladman et al. 2002).

3.3. *2004 VN$_{112}$*

2004 VN$_{112}$ is one of our better-constrained objects, with an orbital arc of 420 d. Its high inclination (25.6°) indicates that it would preferably have been detected by surveys observing far off the ecliptic, where the object is found when near perihelion. The large semimajor axis (315 AU) and eccentricity (0.85) provide a perihelion q of 47.2 AU, a circumstance that places it beyond the dynamical control of any major body currently known in our Solar System. 2004 VN$_{112}$ likely represents a new member of the "extended" scattered disk (ESD; e.g., Gladman et al. 2002). ESD objects have perihelia that detach them from dynamical interactions with Neptune, typically defined as $q > 40$ AU (Lykawka & Mukai 2007).

To ascertain its orbital stability, we generated 1000 clones of 2004 VN$_{112}$ from a multivariate normal distribution incorporating the covariances between orbital parameters derived from the Milani (1999) software. We integrated these for 1 Gyr using the modified version of the SWIFT-RMVS3 integrator (Levison & Duncan 1994) as outlined in Kaib & Quinn (2007). In these integrations, we include the gravitational effects of the Sun, the four giant planets, passing field stars, as well as the Milky Way tide. After 1 Gyr of evolution, we find that the orbits of our clones are relatively unchanged. To be strongly altered by the perturbations from Neptune, the perihelion of 2004 VN$_{112}$ would have to migrate inside ~ 40 AU, and in our simulations we find $\left\langle (\Delta q)^2 \right\rangle^{1/2} = 1.7$ AU for our clones after 10^9 yrs with no bias toward inward or outward migration. Alternatively, this orbit could also be significantly modified by Galactic tides if its semimajor axis grows beyond ~ 1000 AU. This does not occur for any of our clones, with $a = 392$ AU being the largest semimajor axis attained at the end of our simulation. Given these results, we can conclude that this orbit is stable for the history of the Solar System.

The perihelion of 2004 VN_{112} is very near the 2:1 orbital resonance with Neptune. An intriguing possibility is that it was placed on its (currently stable) orbit by a primordial member of the Solar System that was subsequently ejected due to resonant interactions with Neptune. As detailed in simulations by Gladman & Chan (2006), this rogue planet scenario tends to produce higher-inclination objects at smaller semimajor axis. Comparing 2004 VN_{112} to the ensemble of detached TNOs defined by Lykawka & Mukai (2007), we find that 2004 VN_{112} has the second-largest semimajor axis after (90377) Sedna, suggesting it should have an inclination between 12° and 23°. Its inclination of nearly 25.6° (with a fitted uncertainty of 0.004°) is inconsistent with a monotonic decrease in inclination with increasing semimajor axis for the ESD. However, there will be some variance around the relationship, making this a non-definitive constraint. An alternative scenario is that the ESD was formed through perturbations by passing stars, which yields increasing inclinations, eccentricities, and perihelia at larger semimajor axis (e.g., Morbidelli & Levison 2004).

While it is possible that 2004 VN_{112} was a "lucky" find, we proceed with an estimate of the ESD extent with the caveat that this object may not faithfully represent the entire population. 2004 VN_{112} was detected 0.8 mag from the limit of the ESSENCE survey, and 0.3 AU from perihelion. We estimate that such an object would be visible for only 2% of its orbit. Given ESSENCE's areal coverage, a rough estimate of the total number of similar objects or brighter across the entire sky is $\sim 10^5$. The exact number is a function of the unknown inclination distribution for these objects. Simulations of the scattered disk by Morbidelli et al. (2004) suggest that the majority ($70-90\%$) of objects are found at inclinations lower than 25°. However, the current inclination distribution of the ESD is unknown. For our order–of–magnitude estimates here, we adopted a cutoff at 40°. If we further assume an albedo of 0.05 (yielding a diameter of 300 km given its absolute H-band magnitude of 6.4), and a power-law cumulative size distribution with an index of 3, this implies a total number of objects on similar (i.e., detached) orbits, and greater than 100 km in size, of 10^{6-7}. This is similar to the estimates of Gladman et al. (2002) based upon their detection of 2000 CR_{105}.

4. CONCLUSIONS

We report on a data-mining effort that resulted in the discovery and orbital determination of 14 new trans-Neptunian bodies by the ESSENCE Supernova Survey. Only two previously known objects were seen, a high ratio of discovery that highlights the utility and novelty of the search. Each object was detected multiple times over the span of approximately 3 months, with several objects recovered in multiple seasons of the survey. All objects had sufficient data to receive provisional designations from the Minor Planet Center.

Our sensitivity to high-inclination objects was higher than most surveys due to our repeated visits to off-ecliptic fields. We found a substantial number of objects with both large inclinations and high eccentricities. These bodies could only have received such orbits through interactions with a scattering body. 2004 VN_{112} stands out in this regard, having an orbit that detaches it from gravitational interactions with the major bodies of our current Solar System. We have verified that this orbit is stable on 1 Gyr timescales by numerically integrating 10^3 clones. As a member of the extended scattered disk, 2004 VN_{112} provides an additional constraint on theories of external perturbations and early evolution that shaped today's Solar System. In particular, its orbital parameters appear inconsistent with a model in which currently detached objects were previously scattered by a rogue planet. Revealing the overall trend of inclination with semimajor axis will help resolve the origin of the ESD, a study that suggests more observations at even higher ecliptic latitudes. Our detection of 2004 VN_{112} suggests that there are 10^{6-7} objects greater than 100 km in size in the ESD, a vast number whose ensemble properties will help us understand the early evolution of our Solar System.

The success of this study demonstrates that vast amounts of astronomical survey data may be usefully and efficiently mined for Solar System objects. This is a direct result of advances in the fields of image subtraction (Alard & Lupton 1998), data-reduction pipelines (Smith et al. 2002), and data-linking techniques (Kubica et al. 2007). The recent suggestion (White 2007) that dark energy studies are bad for astronomy provides a helpful warning not to let those programs become focused exclusively on a single goal. Our work shows that a deep survey carried out to constrain the dark energy equation of state also contains a wealth of information that can be successfully mined for other valuable science. Observations well outside the ecliptic plane will detect a variety of objects that can provide clues to the evolution of the Solar System, making high ecliptic latitude a region ripe for discovery.

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TABLE 1
Summary of Orbital Parameters for the ESSENCE Sample

Object	*a' (AU)*	*e'*	*i' (deg)*	χ^2*/d.o.f.*	*dT (yr)*	*a*	*e*	*i*	*H*
2003 UC$_{414}$[1]	26.0 (0.1)	0.09 (0.06)	26.4 (0.1)	0.06	0.16	44.9	0.64	25.9	8.3
2006 TK$_{121}$	38.5 (0.7)	0.21 (0.04)	27.27 (0.02)	0.10	0.25	38.4	0.21	27.30	8.1
2003 WN$_{193}$	39.4 (0.4)	0.253 (0.007)	21.62 (0.01)	0.07	0.11	39.4	0.253	21.63	8.5
2003 SR$_{422}$	40.11 (0.04)	0.056 (0.005)	23.914 (0.002)	0.10	1.30	40.07	0.055	23.939	7.1
2007 TZ$_{417}$	41.6 (0.1)	0.14 (0.01)	22.280 (0.004)	0.25	1.14	41.6	0.14	22.310	7.5
2005 SE$_{278}$[2]	42.31 (0.02)	0.110 (0.002)	6.892 (0.001)	0.07	1.24	42.34	0.111	6.894	7.1
2006 QQ$_{180}$[2]	42.7 (9.3)	0.21 (0.36)	9.4 (0.2)	0.12	0.09	42.3	0.18	9.4	6.8
2007 VJ$_{302}$	43.1 (0.2)	0.065 (0.002)	8.70 (0.01)	0.07	1.20	43.1	0.066	8.73	6.8
2003 WO$_{193}$	44.2 (16.6)	0.38 (0.40)	6.626 (0.003)	0.09	0.08	38.6	0.19	6.628	8.3
2007 VK$_{302}$	46.7 (5.7)	0.11 (0.69)	26.3 (0.7)	0.15	0.09	43.5	0.08	28.1	7.0
2007 TD$_{418}$	52.8 (7.0)	0.33 (0.16)	15.091 (0.001)	0.15	0.11	45.2	0.13	15.095	7.9
2007 TC$_{418}$	53.6 (8.3)	0.34 (0.24)	10.6 (0.2)	0.13	0.11	43.1	0.11	11.3	7.6
2007 TA$_{418}$	72.8 (1.6)	0.51 (0.01)	21.962 (0.001)	0.11	1.24	72.7	0.50	21.964	7.2
2007 TB$_{418}$	90.0 (56.9)	0.67 (0.25)	6.55 (0.02)	0.36	0.16	55.3	0.39	6.57	5.8
2003 SS$_{422}$	203 (46)	0.81 (0.05)	16.78 (0.04)	0.16	0.21	196	0.80	16.81	7.1
2004 VN$_{112}$	319 (6)	0.852 (0.003)	25.550 (0.004)	0.04	1.15	319	0.852	25.580	6.4

Note – Orbital parameters for the ESSENCE TNO sample. We include initial orbital parameters and uncertainties derived using the BK00 software : semimajor axis a', shown in AU; orbital eccentricity e'; and orbital inclination i' in degrees. We include the χ^2 per degree–of–freedom from the fit, as well as the orbital arc length in years. We next list the current orbital parameters taken from the MPCORB database provided by the Minor Planet Center, including the absolute magnitude, H, defined as the apparent visual magnitude at zero phase angle and 1 AU distance from both the Earth and Sun.

1 – As outlined in Section 3.1, the BK00 fit is preferred for object 2003 UC$_{414}$.
2 – 2005 SE$_{278}$ and 2006 QQ$_{180}$ were previously discovered by the SDSS-II Supernova Survey (Becker et al. 2008).